Reheating Metastable O'Raifeartaigh Models

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PRD 15 ####

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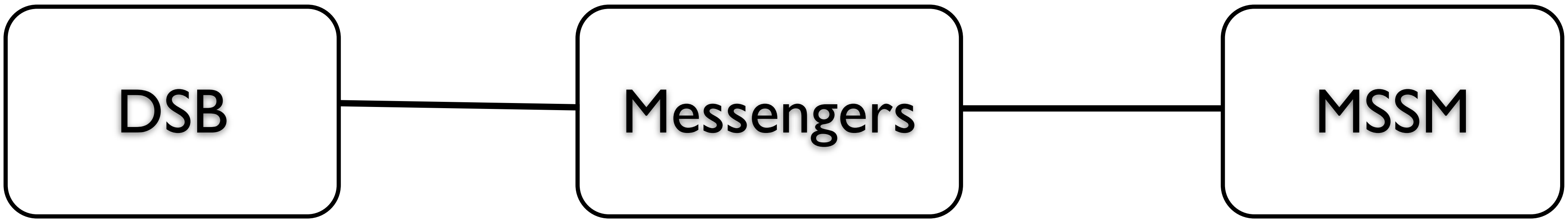
Layout

- Ancient History
- Metastability and ISS
- Finite temperature ISS
- Classic O'Raifeartaigh models
- Conclusions

Usual SUSY breaking scenario



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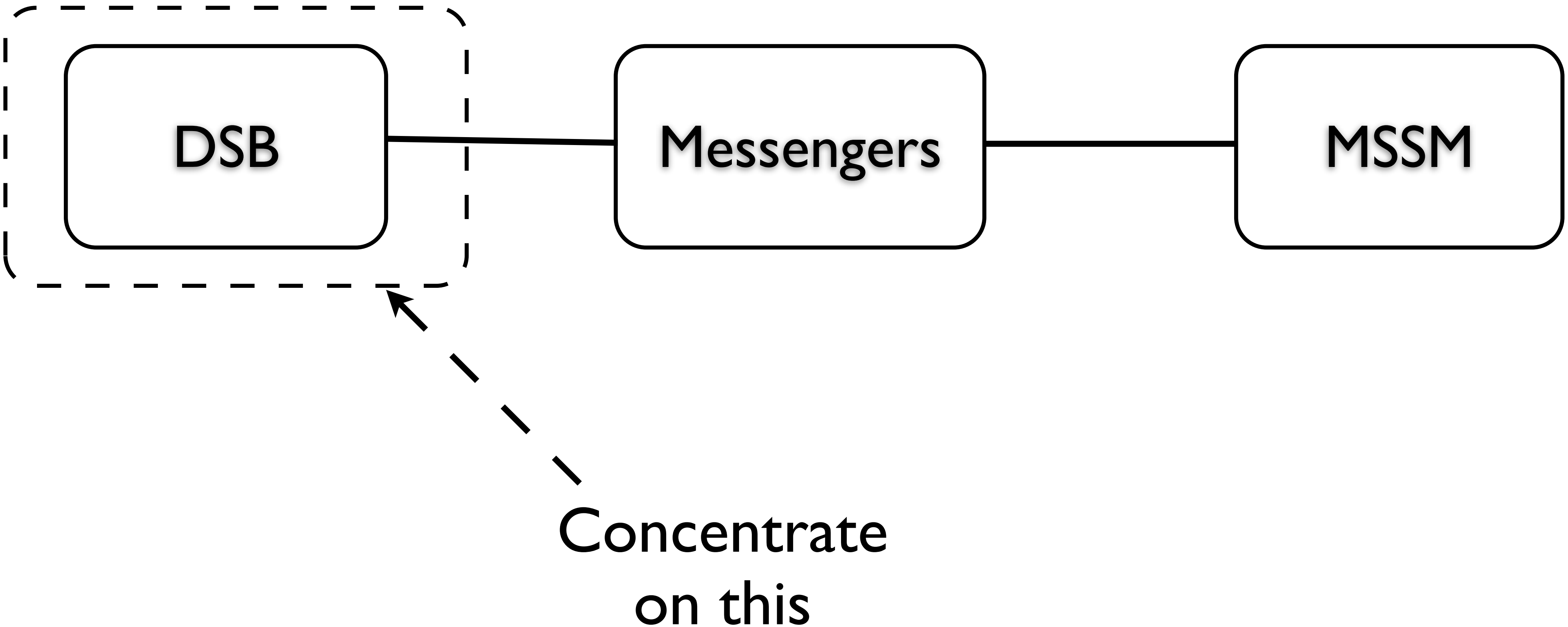

What do we know about DSBs?

- Affleck, Dine, Seiberg: Spontaneously broken non-anomalous global symmetry *but no flat direction* $\Rightarrow$ *SUSY* **probably** *broken*
- Nelson, Seiberg: If symmetry is $U(1)_R$ and general superpotential SUSY **is** broken
- Witten: $\mathrm{Tr}(-1)^F \neq 0 \Rightarrow$ SUSY **not** broken

Witten index of SU(N) is N, one is lead to chiral theories for DSBs.

A typical example: (Dine, Nelson, Shirman)

$$SU(2N+5): \;\; (2N+1)\;\overline{\Box}, \qquad \begin{array}{|c|}\hline \\ \hline \\ \hline \end{array}$$

$$W = \lambda_{ab}\overline{F}^{a}\; A\; \overline{F}^{b} + W_{ADS}$$

Examples:

3,2 model; 4,1 model; SU(5) model

(Intriligator, Seiberg and Shih; JHEP 0604:021,2006)

ISS ask...

Do theories with (global) SUSY vacua also have (local) non-SUSY vacua?

Are they long lived?

If such theories exist are they common?

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YES!

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YES! **SQCD!**

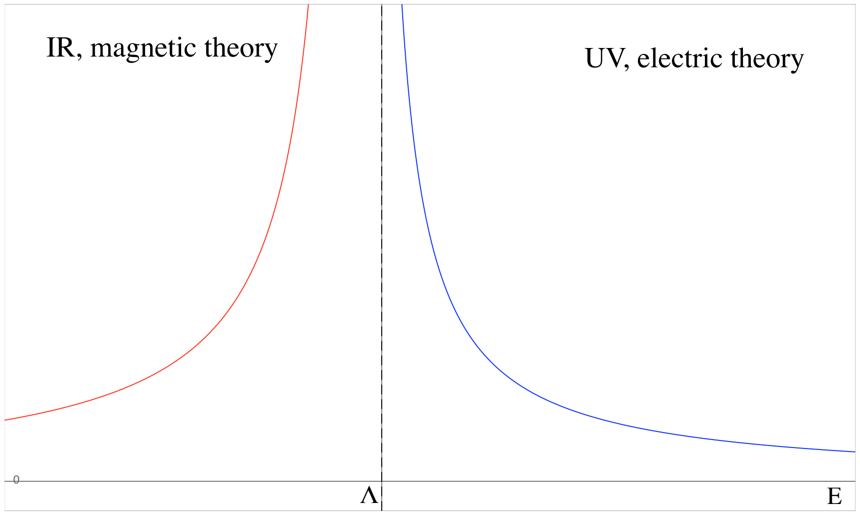
N=1 SQCD, a review

$$SU(N_C) \text{ with } N_F \text{ flavours } \quad (N_C < N_F < \frac{3}{2} N_C)$$

$$Q \sim (\Box_{N_C}, \Box_{N_F}) \qquad Q^c \sim (\overline{\Box}_{N_C}, \overline{\Box}_{N_F})$$

$$W_{el} = m \,\mathrm{tr} Q^c Q$$

Seiberg duality



Magnetic theory

$SU(N)$ with N_F flavours $(N = N_F - N_C)$

$$q \sim (\Box_N, \overline{\Box}_{N_F}) \quad q^c \sim (\overline{\Box}_N, \Box_{N_F}) \quad M = (1, \Box_{N_F}, \overline{\Box}_{N_F})$$

$$W_{mag} = y \ \mathrm{tr}\, qMq^c - \mu^2 \ \mathrm{tr} M$$

$$K = q^\dagger q + q^{c\dagger} q^c + M^\dagger M + \mathcal{O}\left(\frac{\left(q^\dagger q\right)^2}{\Lambda^2}\right)$$

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$\mu^2 = m\,\Lambda$

$$K = q^\dagger q + q^{c\dagger} q^c + M^\dagger M + \mathcal{O}\left(\frac{(q^\dagger q)^2}{\Lambda^2}\right)$$

Kahler corrections will be small if $\mu \ll \Lambda \Rightarrow m \ll \Lambda$

SUSY breaking by rank condition

$$F_{M_i^j} = y\ q_i^a q_a^{cj} - \mu^2\ \delta_i^j$$

$$F_{q_i} = y\ M_i^j q^{cj}$$

SUSY is broken by rank condition

$$\langle M \rangle = 0 \quad \langle q \rangle \sim \mu \mathbb{1}_N \sim \langle q^c \rangle$$

$$F_M \sim \mu^2$$

What about the Witten index?

SUSY breaking by rank condition

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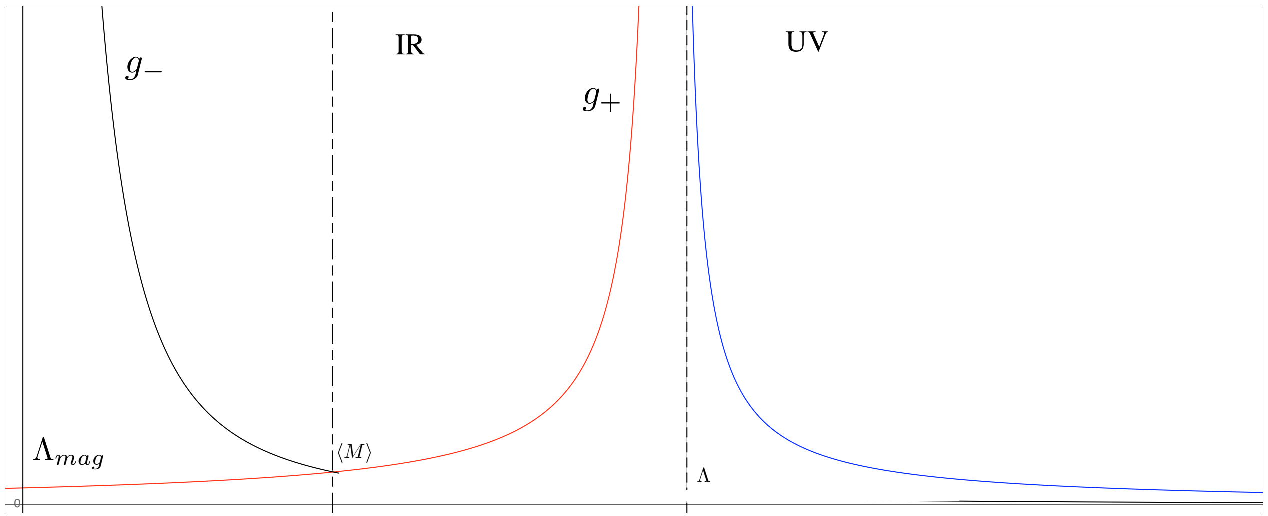
$$F_M \sim \mu^2 \longleftarrow \text{e.g.} \quad \mu \sim 100 - 1000\text{TeV}$$

What about the Witten index?

Below scales $\langle M \rangle$ the magnetic quarks decouple

O'Raifeartaigh model



Strong dynamics at Λ_{mag} generates non-perturbative contribution to the potential

Affleck, Dine, Seiberg

$$W_{IR} = \mu^2 \ \mathrm{tr} M + y \ \mathrm{tr} q M q^c + (\det M)^{1/N} \Lambda^{-a}$$

$$a = \frac{N_F}{N} - 3 \quad (> 0)$$

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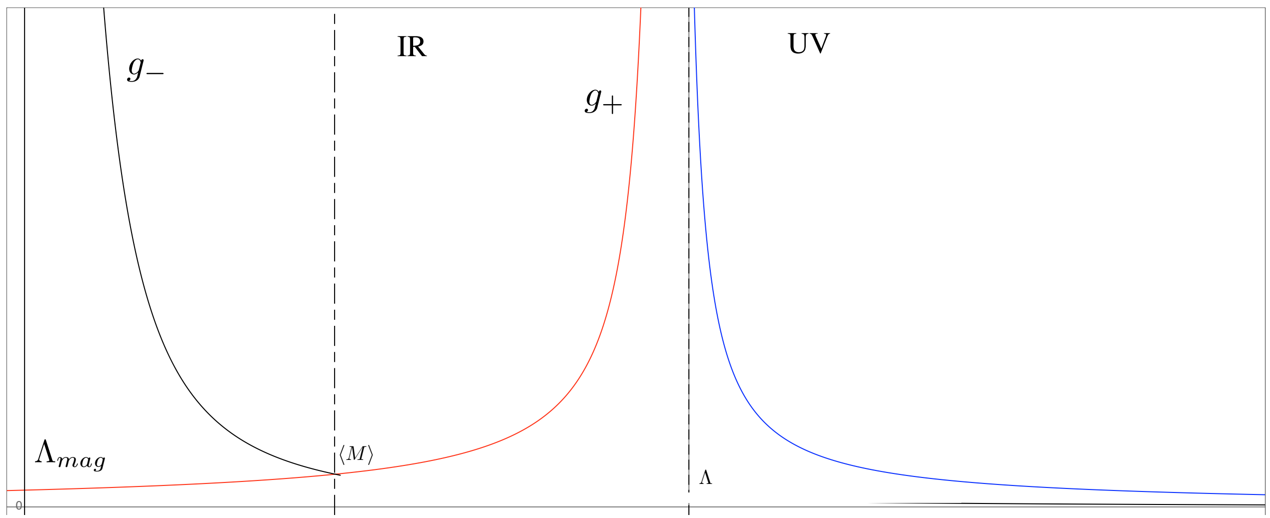
O'Raifeartaigh model



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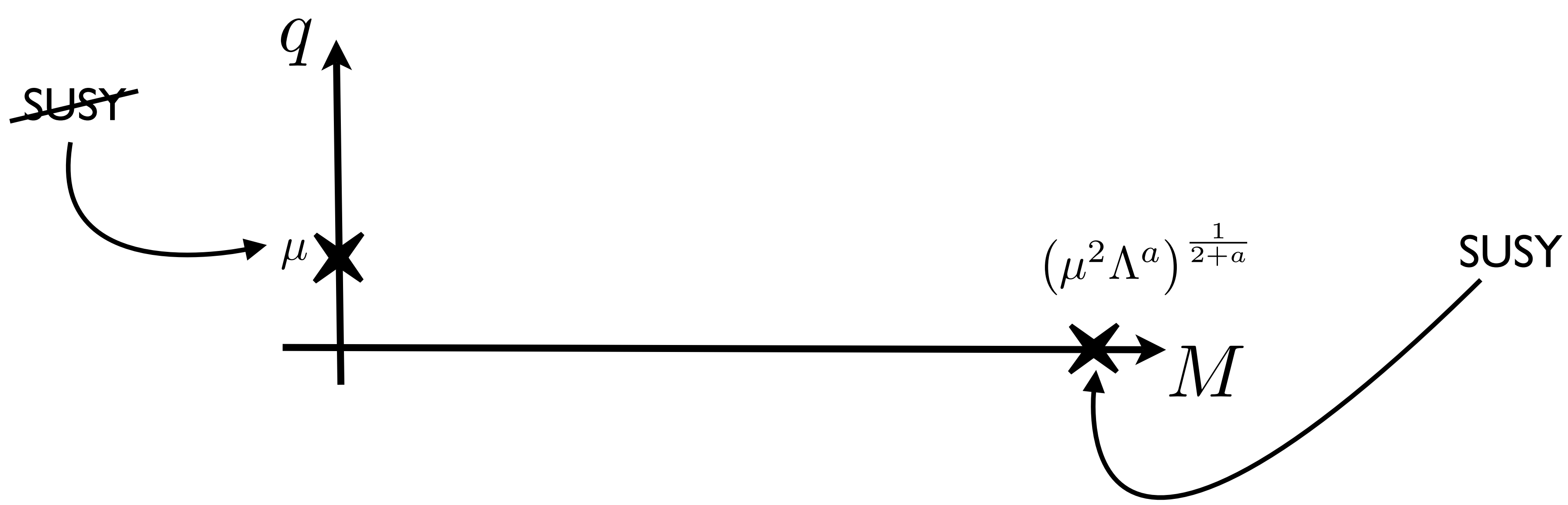
Non-renormalizable op. restores SUSY

$$a = \frac{N_F}{N} - 3 \quad (> 0)$$

Non-perturbative restoration of SUSY

$$M \sim \eta \mathbb{1} \Rightarrow W \sim -\mu^2 + \eta^{3+a}\Lambda^{-a}$$

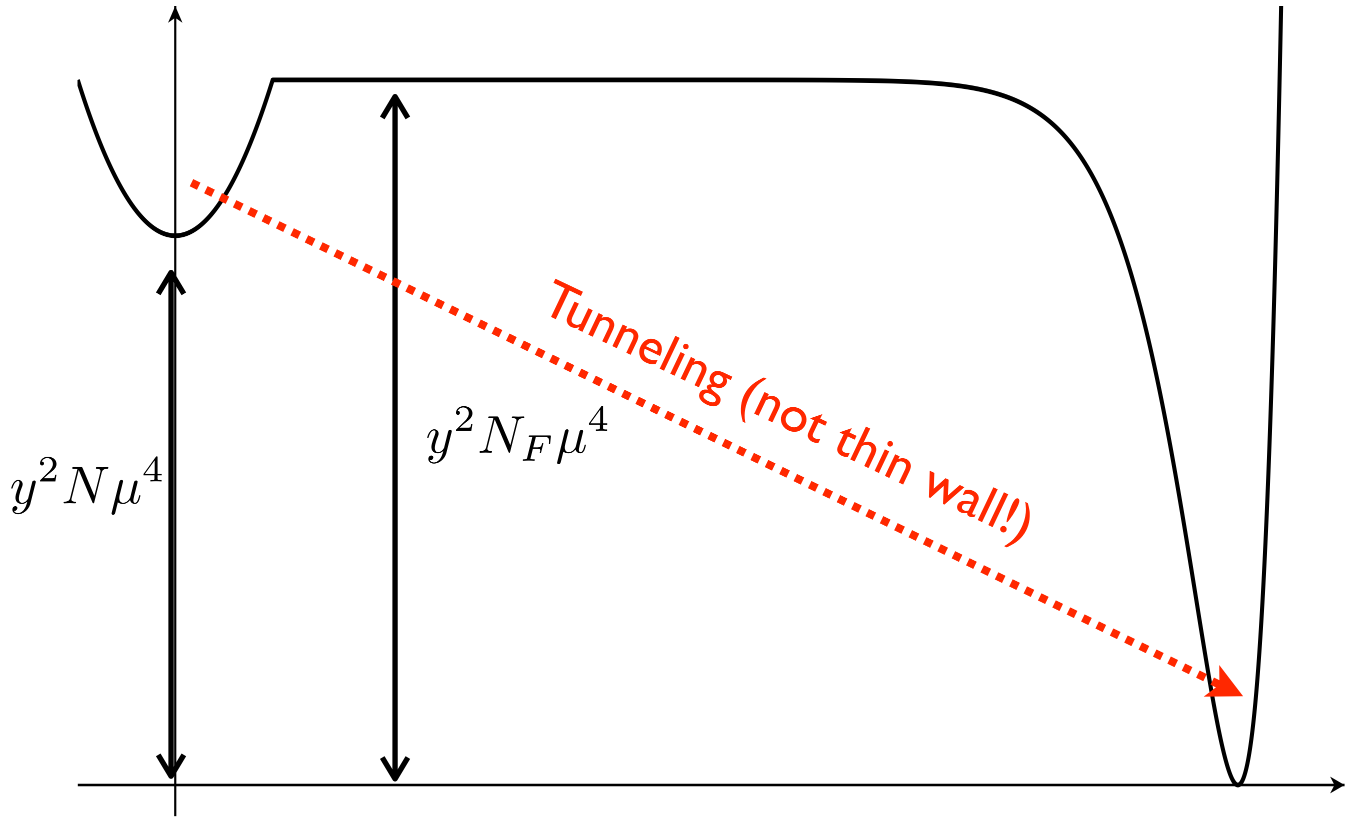
- F-term equations now have a solution, SUSY is unbroken
- SUSY preserving minimum is far out in field space, $\langle M \rangle = \mu \left(\frac{\Lambda}{\mu}\right)^{\frac{a}{2+a}} \mathbb{1}_{N_F}$



Cartoon of the potential

Duncan and Jensen; Phys Lett B291

$$V_0 = N\Lambda^4 \left| \left(\frac{\eta}{\sqrt{N_F}\Lambda} \right)^{2+a} - \frac{\mu^2}{\Lambda^2} \right|^2$$



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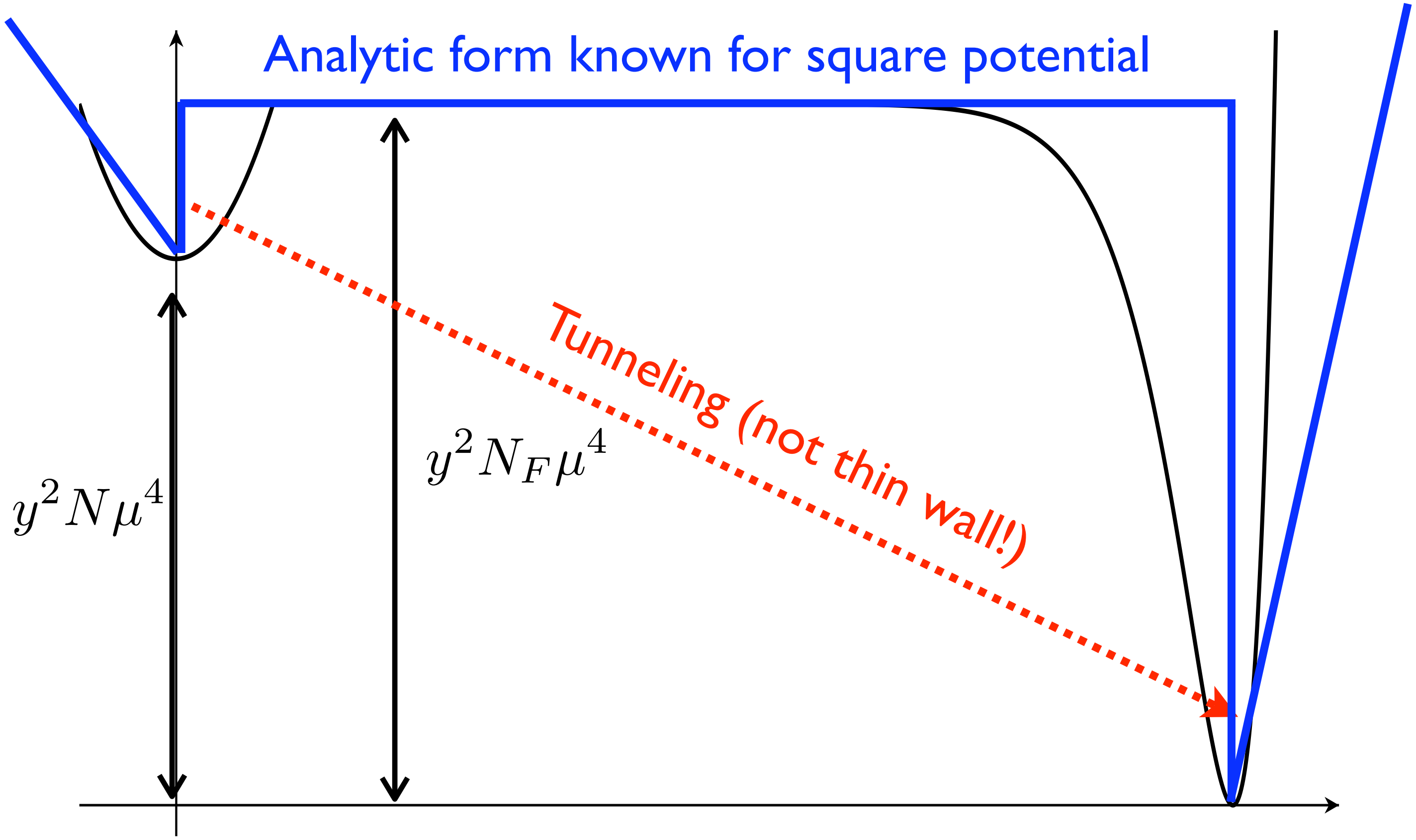


$$\Gamma \sim \mu^4 e^{-S_4}$$

Tunneling rate

$$\Gamma \sim \mu^4 e^{-S_4} \quad \text{with} \quad S_4 \sim \frac{\Delta\eta^4}{\Delta V} \sim \left(\frac{\Lambda}{\mu}\right)^{\frac{4a}{2+a}}$$

Would like $1/\Gamma >$ 14 Gyr !

$$\frac{a}{a+2} \log \frac{\Lambda}{\mu} > 0.73 + 0.003 \log \frac{\mu}{\mathrm{TeV}} + 0.25 \log N$$

$$\text{i.e} \quad \left(\frac{\Lambda}{\mu}\right)^{\frac{a}{2+a}} \gtrsim 2$$

Conclusion I:

•SQCD is a viable, **simple** DSB; very generic

•**If** we start in the SUSY breaking vacuum **and** $\frac{\mu}{\Lambda} \ll 1$ we stay there for a long time.

PART II

- After inflation the visible universe was hot
- The DSB may well have been hot too
- $T \gg \mu$ barrier becomes unimportant
- Minimum of potential is at neither SUSY preserving nor SUSY breaking minimum
- Do we end up in the right place?

Finite temperature field theory

Calculate one loop free energy: $F = E - T\ S$

$$F \sim \begin{cases} V_0(\eta) & T \ll y\eta \\ V_0(\eta) - T^4 + y^2\eta^2 T^2 & T \gg y\eta \end{cases}$$

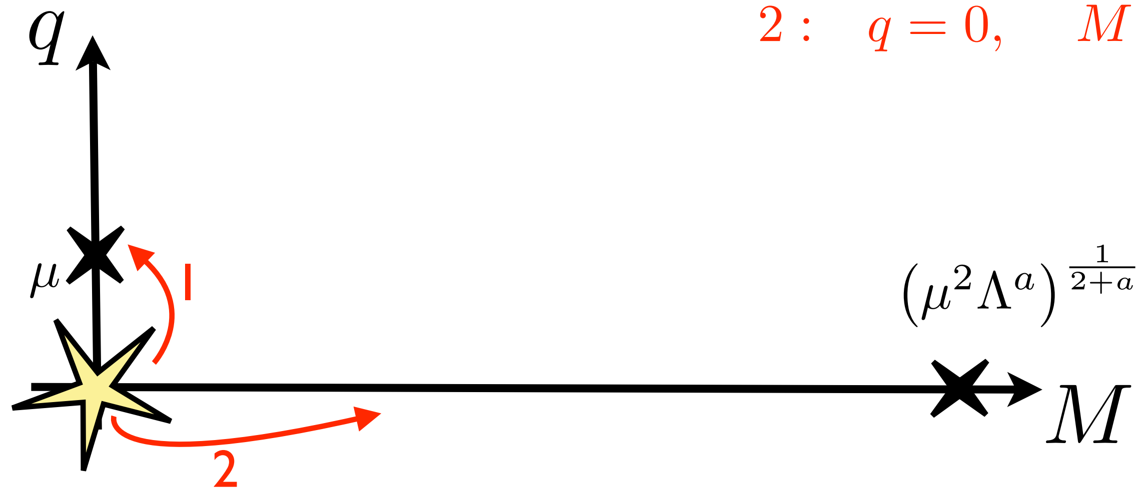
Entropy of light states

Thermal mass term

In ISS as $T \rightarrow \Lambda$ origin becomes minimum

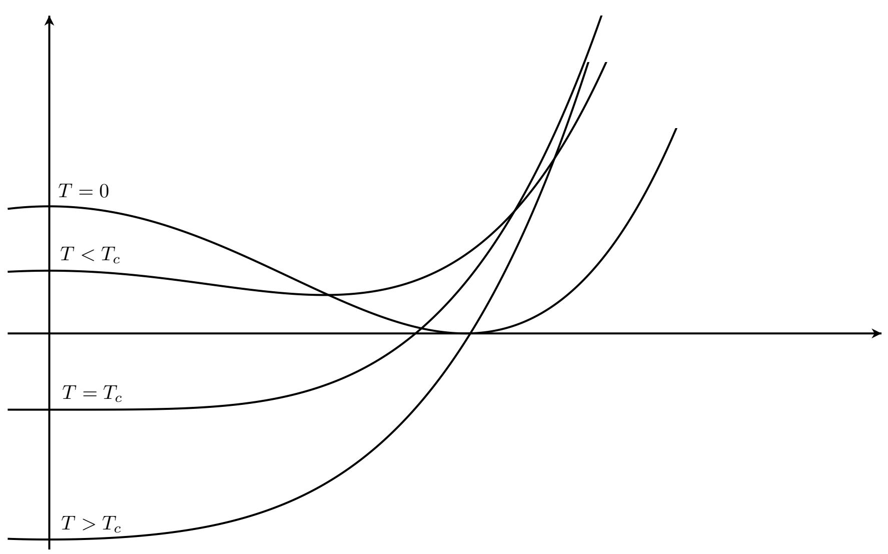
As universe cools what are the order and temperature of the phase transitions in each direction?

$$1:\quad q \neq 0, \qquad M = 0$$
$$2:\quad q = 0, \qquad M \neq 0$$



1: Quark direction $q = q^c = \frac{1}{\sqrt{2N}} (\xi \mathbb{1}_N \ 0)$

$$V_0 = N \left(\frac{y}{N^2} \xi^2 - \mu^2 \right)^2 \to V_0 - c_0 N_F^2 T^4 + (c_1 g^2 + c_2 y^2) N \xi^2 T^2$$



Second order
phase transition

$$T_c \sim \frac{\mu}{\sqrt{y} N}$$

2: Meson direction $M = \frac{\eta}{\sqrt{N_F}}\mathbb{1}$

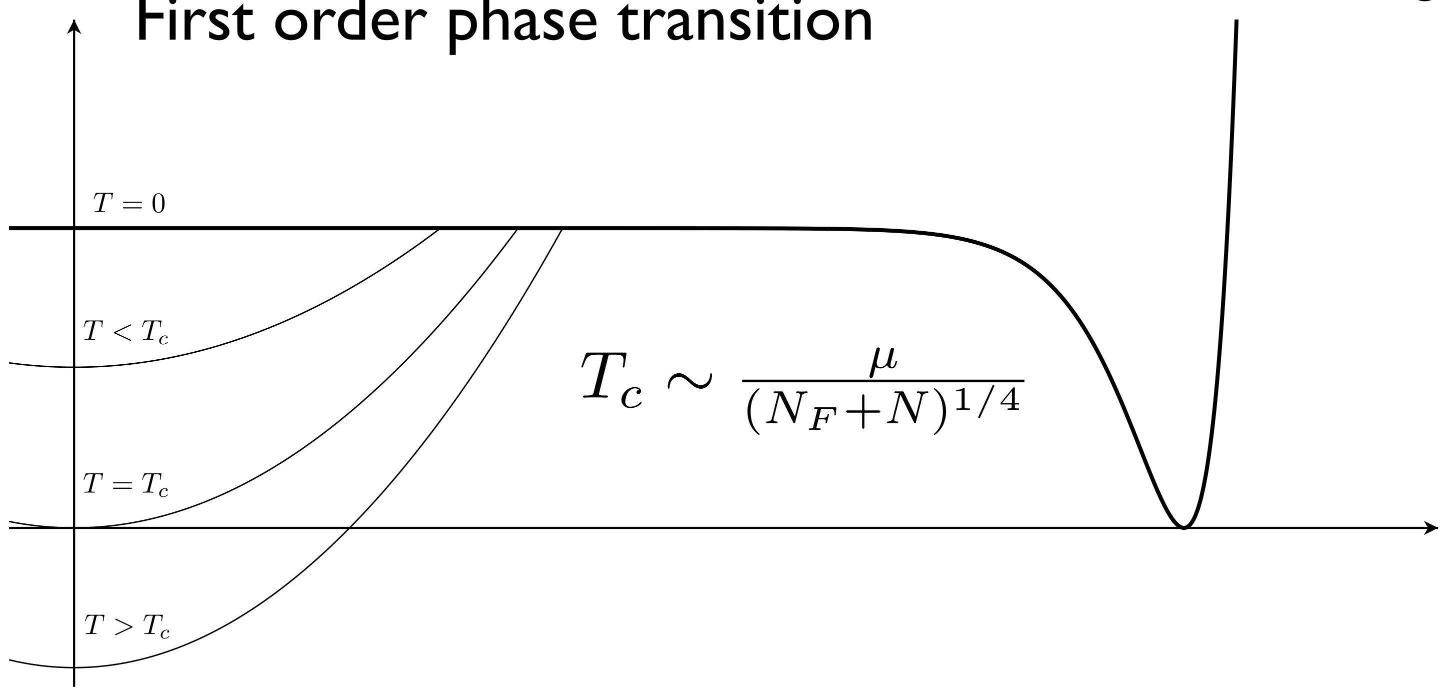
$$V_0 = N\Lambda^4 \left| \left(\frac{\eta}{\sqrt{N_F}\Lambda}\right)^{2+a} - \frac{\mu^2}{\Lambda^2} \right|^2$$

quarks

$$V \sim \begin{cases} \mu^4 + c_1\, y^2 N \eta^2 T^2 - c_0 (N N_F + N^2) T^4 & T \geq \Lambda_m(\eta) \\ V_0 + c_1\, y^2 N \eta^2 T^2 - c_0 N N_F T^4 & T \geq y\eta \\ V_0 & T < y\eta \end{cases}$$

gauge bosons

First order phase transition



$$T_c \sim \frac{\mu}{(N_F + N)^{1/4}}$$

Tunneling time

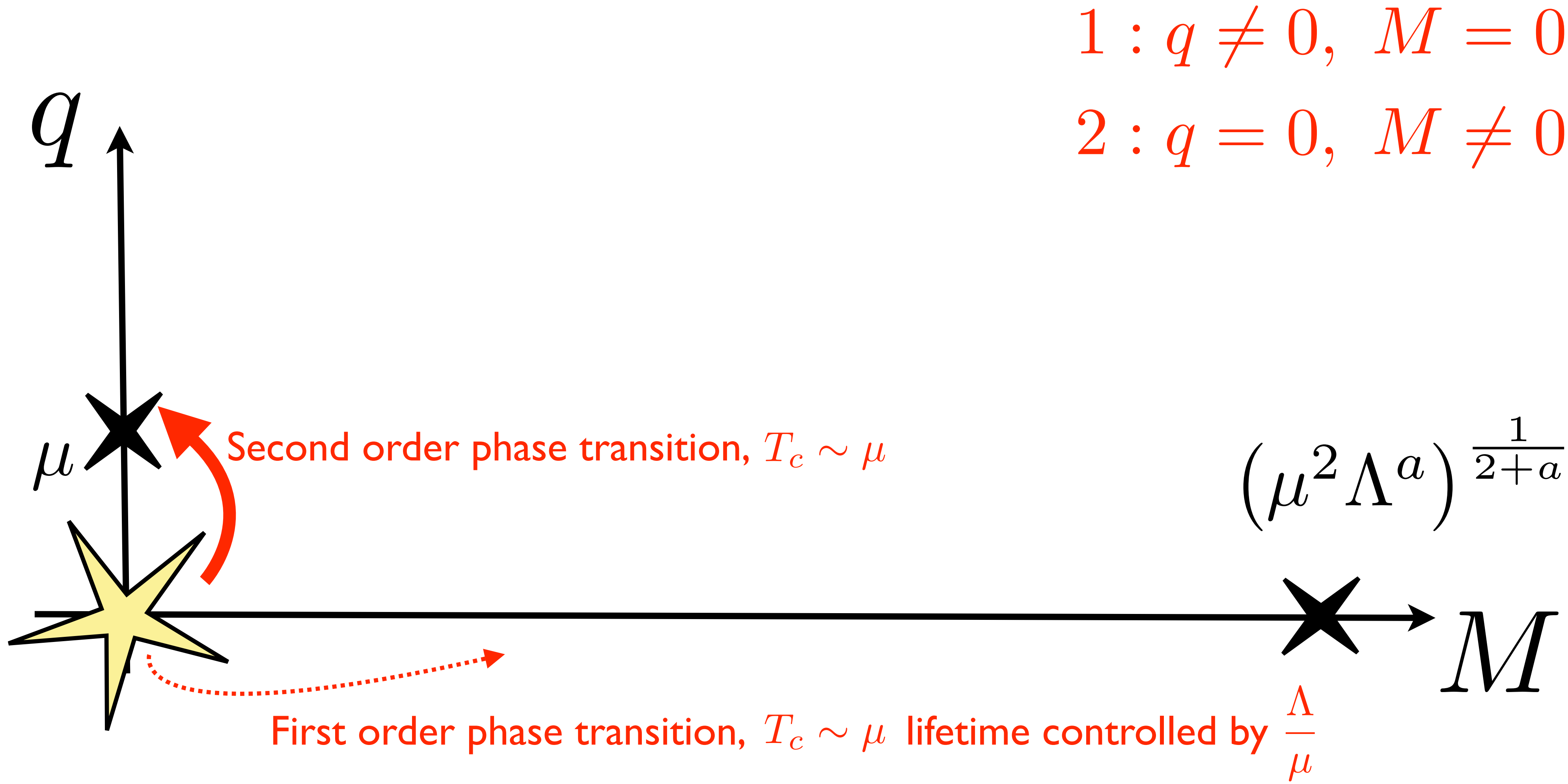
- Use square approximation, now at finite temperature, $\Gamma \sim T^4 e^{-S_3/T}$

Different power from zero temp.

$$S_3 \sim \left(\frac{\Lambda}{\mu}\right)^{\boxed{\frac{3a}{2+a}}}$$

- Want universe still in false vacuum, $\Gamma(T) a^3(T) \mathcal{V} \Delta t \approx 0$

$$\frac{a}{a+2} \log \frac{\Lambda}{\mu} \gtrsim 0.64 - 0.001 \log \frac{\mu}{\text{TeV}} + 0.17 \log N$$



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$2: q = 0, \ M \neq 0$
q
μ
Second order phase transition, $T_c \sim \mu$
$\left(\mu^2 \Lambda^a\right)^{\frac{1}{2+a}}$
M
First order phase transition, $T_c \sim \mu$ lifetime controlled by $\frac{\Lambda}{\mu}$

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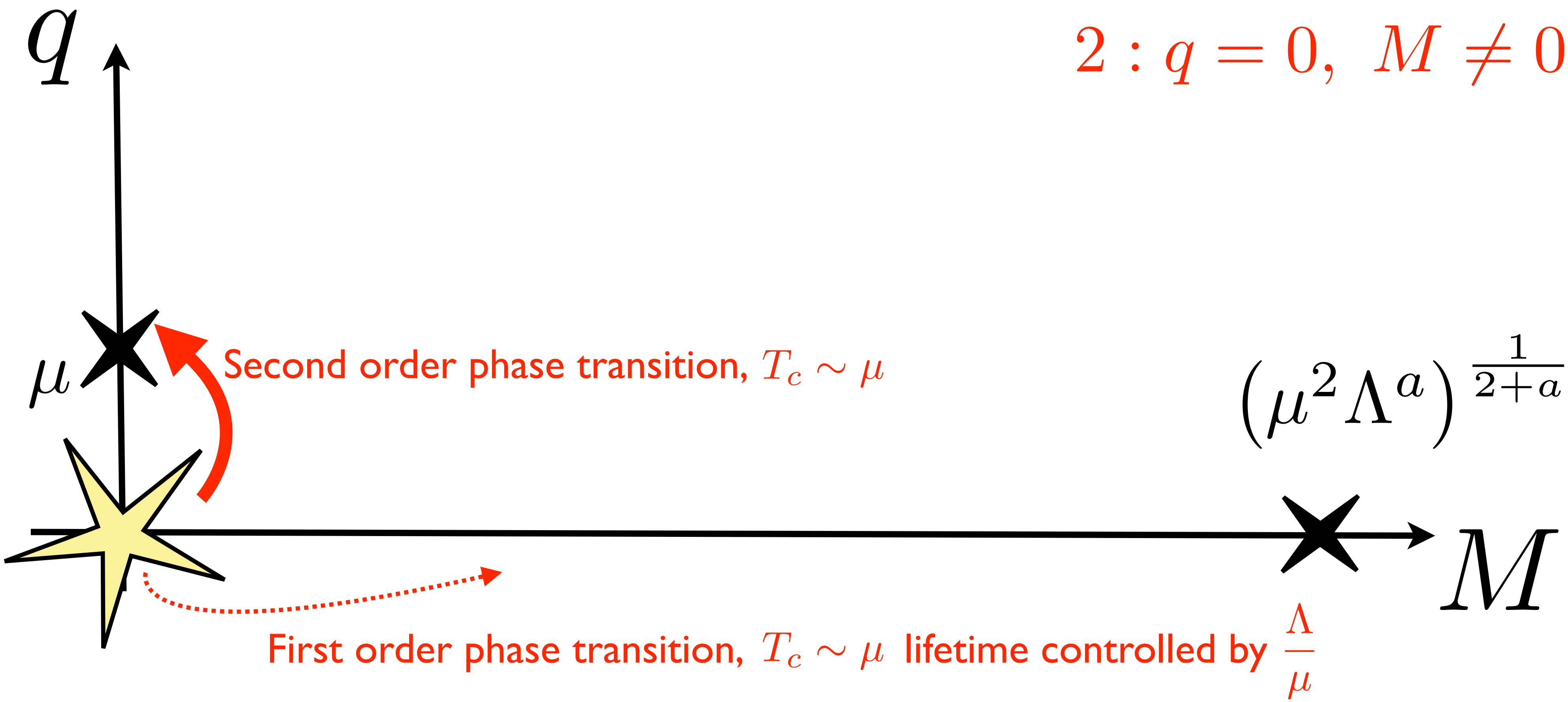

If you satisfy the zero-temperature lifetime requirement of ISS then you automatically will get the correct cosmology

"Classic" O'Raifeartaigh Models

Dine, Feng and Silverstein; hep-th/0608159

$$W = m\,\psi\psi^c + \lambda\, Z(\psi^2 - \mu^2) \qquad (m \gg \mu)$$

Origin is minimum and SUSY is broken, $F_Z = \lambda\,\mu^2$

Using "retro-fitting" to explain the small scale μ leads to

$$W = m\,\psi^c\psi + \lambda Z\left(\psi^2 - \mu^2\right) + \frac{1}{2}\epsilon\mu Z^2$$

A new SUSY preserving minimum develops at large field value, $Z_{susy} = \epsilon^{-1}\mu$

z

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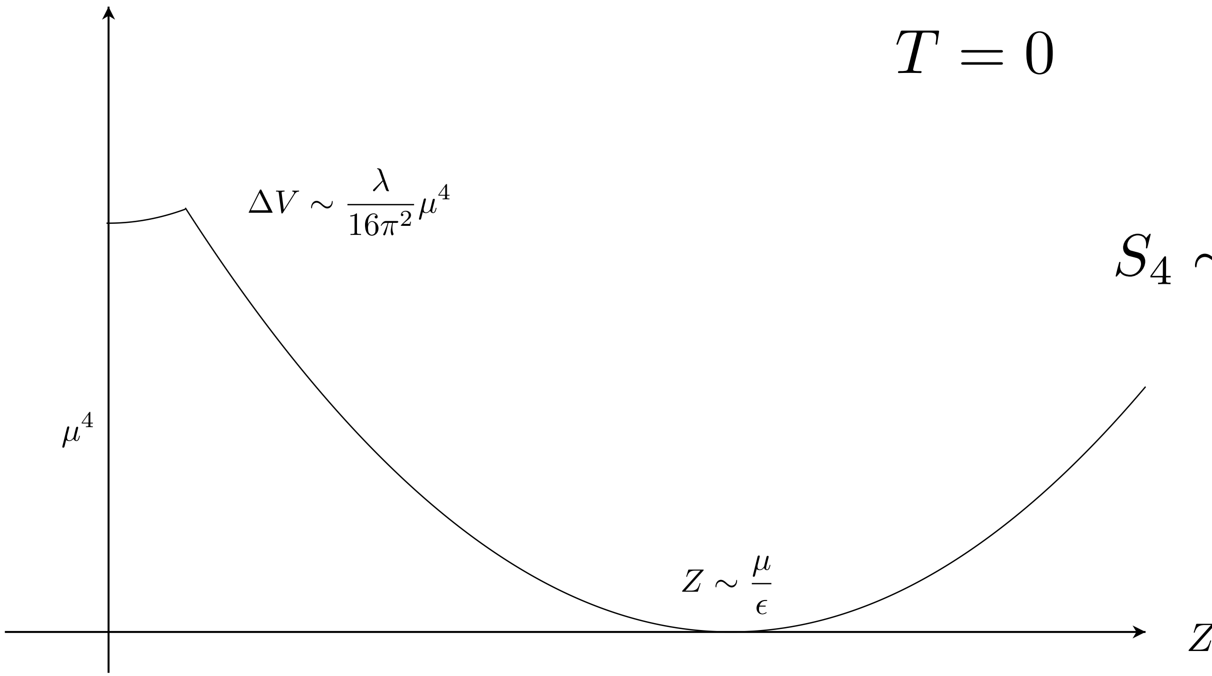
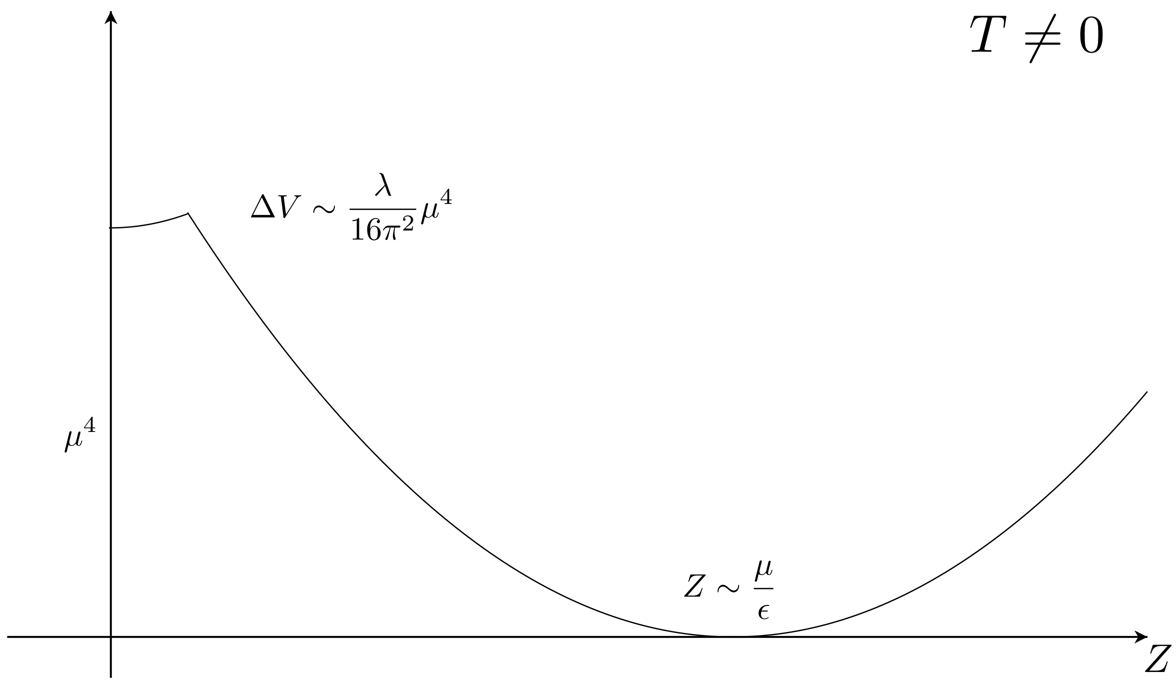
$T = 0$



$$S_4 \sim \left(\frac{\lambda^2}{16\pi^2}\right)^3 \epsilon^{-4}$$

$T \gg m$: Origin is stable

$\mu < T < m$: Origin no longer stable, barrier very small



$$S_3/T \sim \left(\frac{\lambda}{4\pi}\right)^5 \epsilon^{-3}\,\frac{\mu}{m}$$

No extra light states at the origin: additional finite temperature constraint

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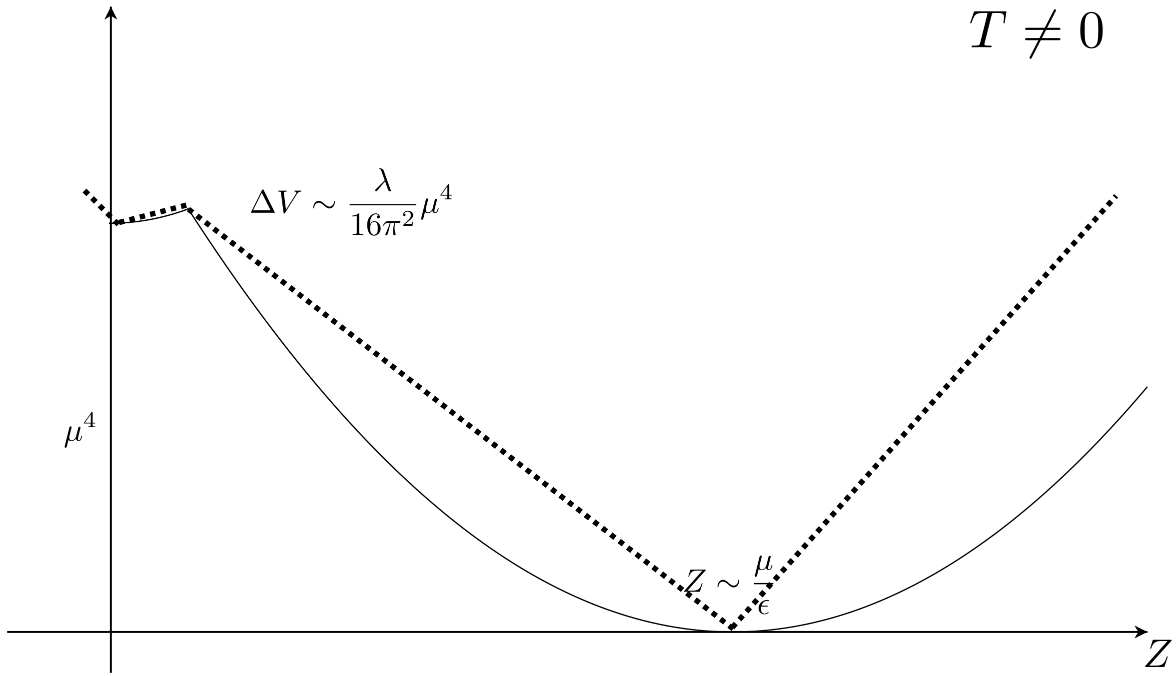

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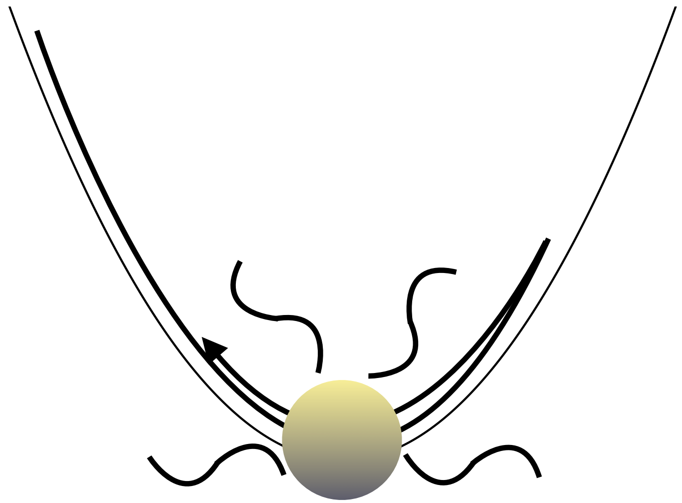
Thermalization

ISS like models quickly thermalize

- e.g. Imagine after inflation DSB is cold, $T \ll H$
- Oscillations of $Q \sim H$ dominate energy density
- Quickly dampened by particle production at origin L. Kofman et al. JHEP5 (2004) 030
- True also in magnetic theory



Conclusions

- SQCD provides a simple, generic DSB sector
- Provided there is a hierarchy $(m \ll \Lambda)$ of scales our vacuum is long lived, at zero temperature
- Starting at the origin there are two phase transitions to the two minima. Because of the extra light states at the origin it evolves to the correct minimum
- No (parametrically) different constraints, from thermal history
- Retro-fitted O'Raifeartaigh models do not satisfy these conditions, there is no entropic cost to moving away